

EVALUATION OF THE NASA BALL ON PLATE TRIBOMETER AS AN ANGULAR CONTACT BALL BEARING

Edward Kingsbury

Interesting Rolling Contact

Walpole, MA 02081

ABSTRACT

The NASA Ball on Plate Tribometer (BoPT) is a bench tester for ball bearing boundary lubricants. This paper shows that BoPT operation is described by suitable specialization in published first order kinematic equations for Angular Contact Ball Bearings (ACBB). Thus, since the BoPT is in fact a ball bearing, transfer of BoPT test results to real bearing applications is meaningful. We also discuss some second order effects present in both BoPT and ACBB operation.

INTRODUCTION

The NASA Ball on Plate Tribometer was developed as a bench test for boundary lubricants in ball bearings. It has been described in general in Reference 1 and in detail in Reference 2. Many people distrust tribological bench tests for a variety of reasons, including inappropriate geometry. The BoPT is a real ball bearing (albeit of unusual design) whose peculiarities can be quantitatively analyzed. Its running conditions can be adjusted to match a wide range of bearing applications, and controlled well enough for reproducibility. BoPT test results have shown definite distinctions amongst boundary lubricants. This paper compares the BoPT and ACBB, listing

9 similarities and differences between them as an aid in evaluating boundary lubrication effects in real bearings.

FIRST ORDER KINEMATIC ANALYSIS, ACBB

The following has been abstracted from Reference 3. An ACBB has five components: inner race, outer race, ball set, ball retainer/separator/cage, and lubricant. Races and balls are arranged as shown in Figure 1. A preload, parallel to the bearing spin axis, pushes inner and outer races against each other through the ball set. Ball diameter d , pitch diameter E , and race curvatures are controlled so that the preload is carried across the balls along lines of contact that define the contact angle B .

The two races can be given independent angular velocities represented by vectors I and O , parallel to the spin axis, of any length and in either direction. The bearing as a whole is then said to have total speed S and average speed A :

$$S = I - O \quad 1$$

$$A = \frac{1}{2}(I + O) \quad 2$$

Total speed is the algebraic difference in race rates and measures the shear in the bearing. For example, if $S = 0$ the whole bearing assembly turns as a solid wheel. Average speed is the arithmetic average of the race rates.

As a result of the imposed race rotations, the balls orbit around the bearing spin axis at the group angular velocity, represented by another vector G , parallel to the bearing axis. Assuming equal inner and outer contact angles

(true for a stationary bearing), and “roll without slip” at the ball-race contacts we get:

$$G = A + S \frac{d \cos B}{E} \quad 3$$

At the same time each ball rotates about its own center at its “spin” angular velocity s :

$$s = S \frac{E^2 - d^2 \cos^2 B}{2Ed} \quad 4$$

However, s is not parallel to the other angular velocities; instead it is normal to the line of contacts, at $\pi - B$ from the bearing spin axis. This misalignment in angular velocities introduces pivot (see below) at all ball race contacts.

The coefficient of S in Eq. (4) is constant, a function of bearing geometry only, and is called ρ , the basic speed ratio of the bearing. Eq. (4) shows that ball spin rate equals ρ times total speed, no matter what the particular combination of race rotations (and the resulting group orbit rate) might be.

Two quantities related to lubricant degradation in ACBB operation are contact pivot p and contact severity σ . Pivot is the component of relative angular velocity of two bodies in contact normal to their plane of contact. It damages lubricants in an ACBB by inducing pivoting slip in the high pressure ball-race contacts (Reference 4). The sum of the pivot magnitudes at the inner and outer race contacts on a single ball in an ACBB is:

$$\sum |p_{i,o}| = S \sin B \quad 5$$

depending only on total speed and geometry.

Severity is the rate at which friction energy is deposited in a contact, and is important because it measures the chemical degradation of the lubricant:

$$\sigma = \mu \int_H P v dH$$

Here μ is friction coefficient, H is the (elliptical) Hertz area, P is local pressure and v is local slip velocity (proportional to pivot times the local radius vector from the center of the Hertz footprint).

A conventional ball bearing is fitted with a ball retainer. Its mechanical functions are to retain the ball set during bearing assembly and to separate the balls so that they cannot touch each other during operation. Since the retainer rotates once each time the ball set orbits, it shares the group angular velocity G . The retainer is located radially by one of the races (determined by bearing design) and slides continuously against that race. A particular ball slides against its pocket in the retainer if its orbit speed is faster or slower than the average for the set. There is no easy way to determine either the retainer-race force, the ball-pocket contact force system, or their time dependencies in any real bearing application.

FIRST ORDER KINEMATIC ANALYSIS, NASA BoPT

The BoPT also has five components: top plate, bottom plate, guide plate, ball set and lubricant, set up as shown in Figure 2. Three equally spaced balls of diameter d roll between a stationary bottom plate and a top plate rotating at T . The balls carry an applied axial load W from plate to

plate (analogous to preload in an ACBB). Top and bottom contact angles are both $\pi/2$, automatically satisfying the second ACBB kinematic assumption.

To first order the ball track is circular, having a pitch diameter of $2 R$ (analogous to E). The Hertz contact areas are circular, each radius r_H depending on the load being carried. This simple geometry gives a closed form for the severity integral. To substitute in the ACCB formulas for the BoPT we associate the rotating top plate with an outer race and the fixed bottom plate with a stationary inner race, analogous to outer race rotation. Table I lists the results of the substitution:

TABLE I

ACCB & BoPT COMPARED FOR FIRST ORDER KINEMATICS

VARIABLE	ACBB	BoPT
S , total speed	$I - O$	T
A , average speed	$(I + O) / 2$	$T / 2$
G , ball orbit rate	$A + S (d \cos B) / 2$	$T / 2$
B , contact angle	B	$\pi / 2$
ρ , basic speed ratio	$(E^2 - d^2 \cos^2 B) / 2 E d$	R / d
s , ball spin rate	ρS	$(R / d) T$
$\Sigma p_{i,o} $, absolute pivot sum	$S \sin B$	T
σ , severity	$\mu \int_A P v dA$	$3 \pi / 32 (\mu T W r_H)$

The results in the last column are identical with those rigorously derived in Reference 2 for the BoPT under the single assumption of roll without slip. Therefore it is completely reasonable to apply BoPT results to ACBB ball-race problems, at least to first order. Quantitative correspondence in rolling conditions within the Hertzian contacts can be established through severity calculations (friction coefficient evaluation is discussed below).

Note that the ball orbit rate in the BoPT is independent of ball size and load. The balls maintain their spacing without a separator, and none is used in the BoPT.

SOME SECOND ORDER EFFECTS

TRANSVERSE MICROCREEP

BoPT - Spiral Track

The most important second order effect in the BoPT is that the balls take a spiral rather than a circular track. The spiral is attributed to elastic microcreep (Reference 5), and would eventually cause the balls to fall from between the flats if ignored. Figure 2 shows the guide plate assembly used to correct for this problem. Each ball, starting at R, spirals outward and contacts the guide plate at an increased pitch radius near the end of each orbit. It then rolls along the guide plate in a straight line track (called the "scrub") back to its original radial position at R, and repeats. Since the guide plate retains the ball set between the plates, the BoPT is a separatorless, but not a retainerless ball bearing. Figure 3 is a photograph of the spiral-scrub combined track, with overlain angular velocities for the ball.

Kinematics in the scrub is analyzed in detail in Reference 2. The scrub generates gross slip not present in an ACBB, however the magnitude,

variation, location, and duration of scrub slip are well defined and easily accounted for when analyzing BoPT results. The guide plate is mounted on a force transducer which measures friction during each scrub (thereby providing friction coefficient for severity calculations).

ACBB - Blocking

It has been suggested that the balls in an ACBB also undergo transverse microcreep, rolling outward and up the groove side into a pinched position at increased contact angle. The effect is called blocking, and has been cited in discussions of high torque events in space mechanisms. (References 5,6). In principle, blocking could be directly measured in the BoPT if a grooved track were machined into the bottom plate. A small upward displacement of the top plate during the first few revolutions would establish the effect.

ANGULAR VELOCITY DEFICITS

BoPT - Group Orbit Rate

The theoretical ball group orbit rate in the BoPT is half the top plate rate (line 3 in Table I). However, measurements show the actual rate to be slightly less than the theoretical rate, typically 0.03% less for liquid lubricants. The deficit appears to depend on the type of lubricant in use. In particular, a deficit at least an order of magnitude smaller was found using a solid film lubricant. The origin of this deficit in a boundary lubricated system is not understood at present, although it evidently is a manifestation of circumferential slip between ball and plate. Perhaps it will prove necessary to explore viscous or plastic effects in boundary films.

ACBB - Ball Spin Rate

A second order angular velocity deficit is also present in ACBB operation. Measurements show that balls spin slightly slower than their theoretical rate, and that the deficit is larger for thicker lubricating films. The effect has been attributed to the presence of circumferential rheologic slip between balls and race, and for a parched EHL film, seems a reasonable consequence of viscosity or plasticity (Reference 4). A correspondence between increased spin rate and decreased measured film thickness has been established (Reference 8).

SUMMARY

The BoPT is a separatorless, but not a retainerless angular contact ball bearing, described to first order by standard bearing equations. It generates short, well-characterized bursts of load/slip not present in an ACBB, that for its part generates continuous, poorly defined load/slip at cage contacts that are not present in the BoPT. The BoPT measures a friction coefficient that can be used to quantify contact conditions likely to damage boundary lubricants via contact severity. A severity calculation can be used to connect BoPT bench test conditions with real bearing conditions.

At least two second order effects are shared by the BoPT and ACBB: transverse microcreep and angular velocity deficit. Because of its simple rolling conditions and accessible components the BoPT offers an easy experimental means of studying these interesting issues.

REFERENCES

1. Kingsbury, E., S. V. Pepper and B. Ebihara, **Lubrication of Slow Rolling Contacts – the NASA Ball on Plate Tribometer**, , presented at the ASME/STLE Joint Tribology Conference, San Francisco, 1996, in press.
2. Pepper, S. V., E. Kingsbury and B. Ebihara, **A Rolling Element Tribometer for the Study of Liquid Lubricants in Vacuum**, NASA TP-3629, October, 1996.
3. Kingsbury, E., **First Order Ball Bearing Kinematics**, ASLE Trans., v. 28, April, 1985, pp. 239-244.
4. Kingsbury, E., **Influences on Polymer Formation Rate in Instrument Ball Bearings**, STLE Trib. Trans. v. 35, January 1992, pp. 184-188.
5. Johnson, K. L., **Contact Mechanics**, Cambridge University Press 1985, Cambridge, pp. 242-283.
6. Todd, M. J., **Investigation of Torque Anomaly in Oscillating PDM Bearings**, European Space Agency Report No. 49, 1981.
7. Loewenthal, S. H., **Two Gimbal Bearing Case Studies: Some Lessons Learned**, 22nd Aerospace Mechanisms Symposium (1988), NASA Conference Publication 2506, pp. 253-269.
8. Kingsbury, E., Schritz, B., and Prah, J., **Parched Elastohydrodynamic Lubrication Film Thickness Measurement in an Instrument Ball Bearing**, STLE Trib. Trans., v. 33, pp. 11-14 (1990).

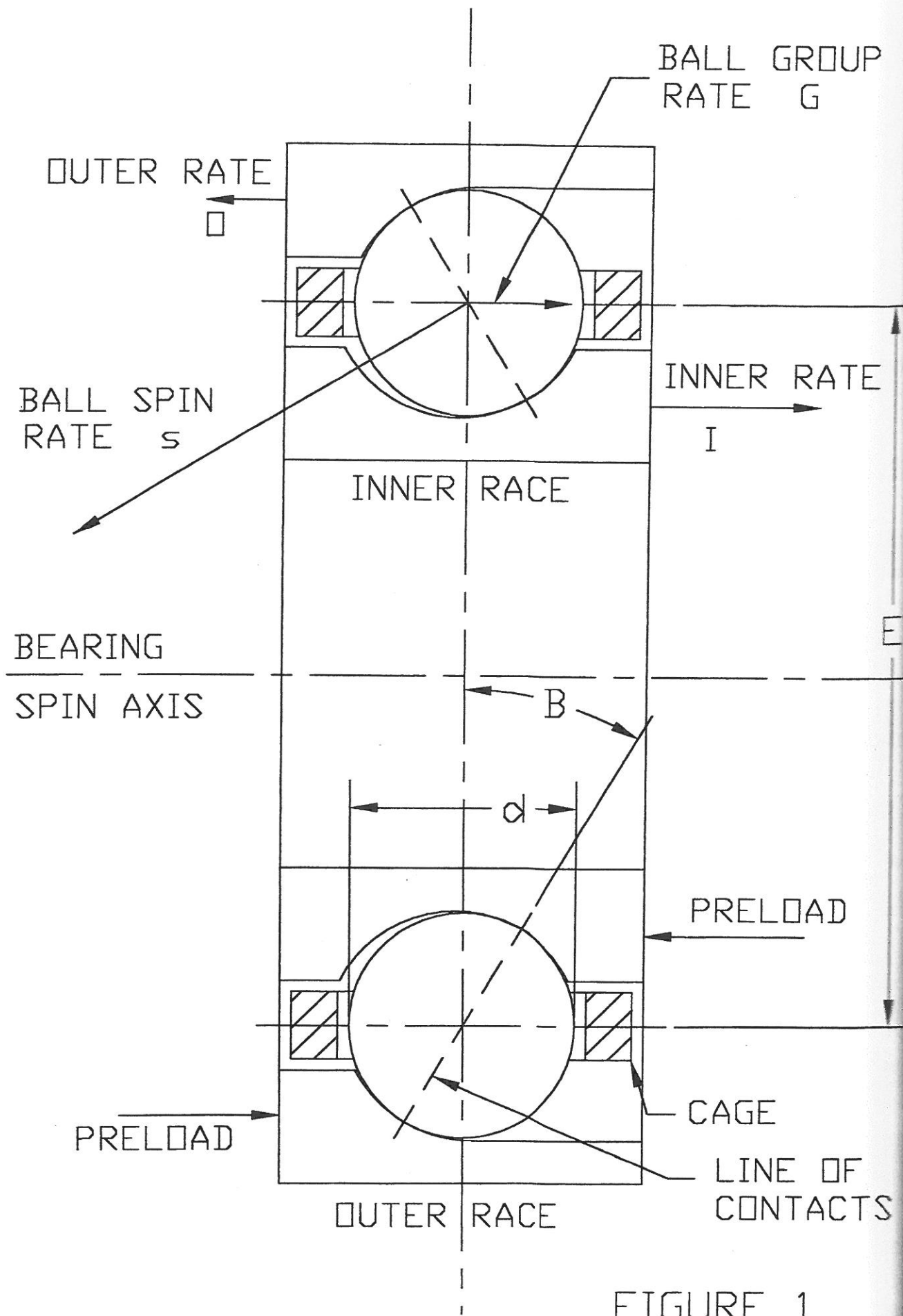


FIGURE 1

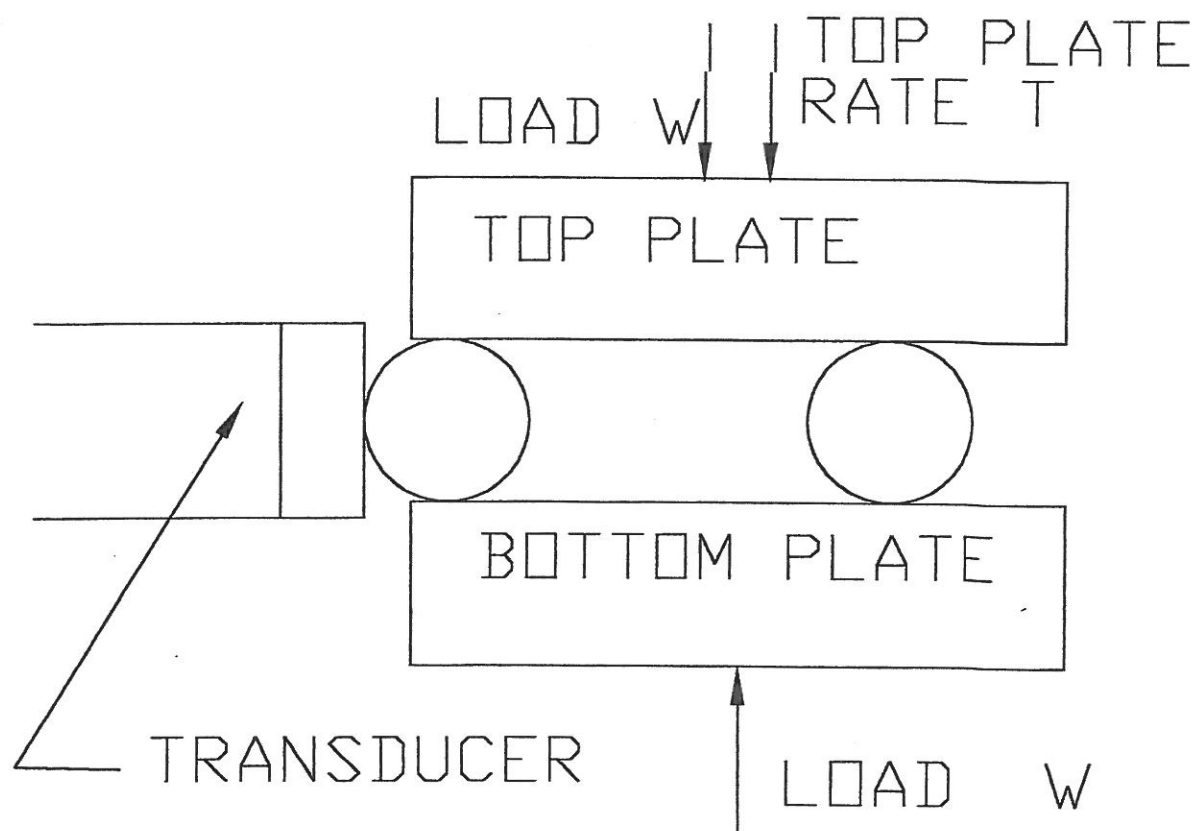
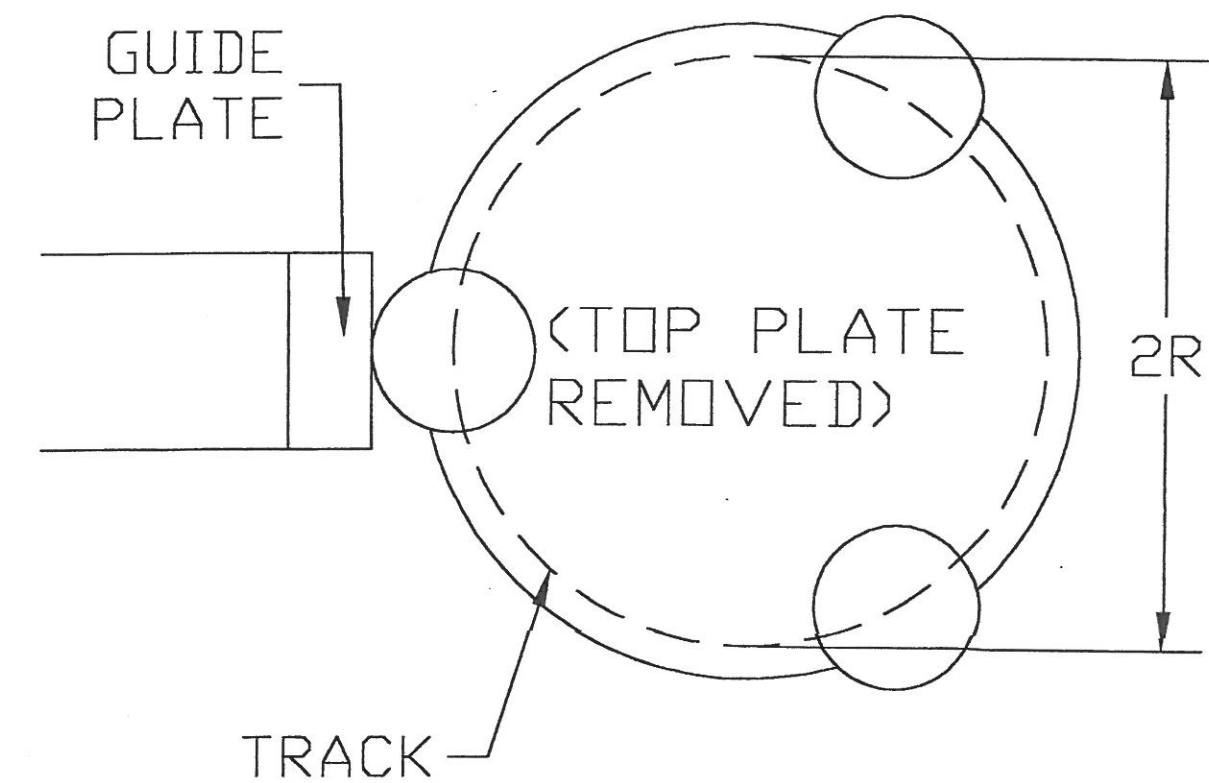


FIGURE 2

Ball Motions In The Ball On Plate Tribometer

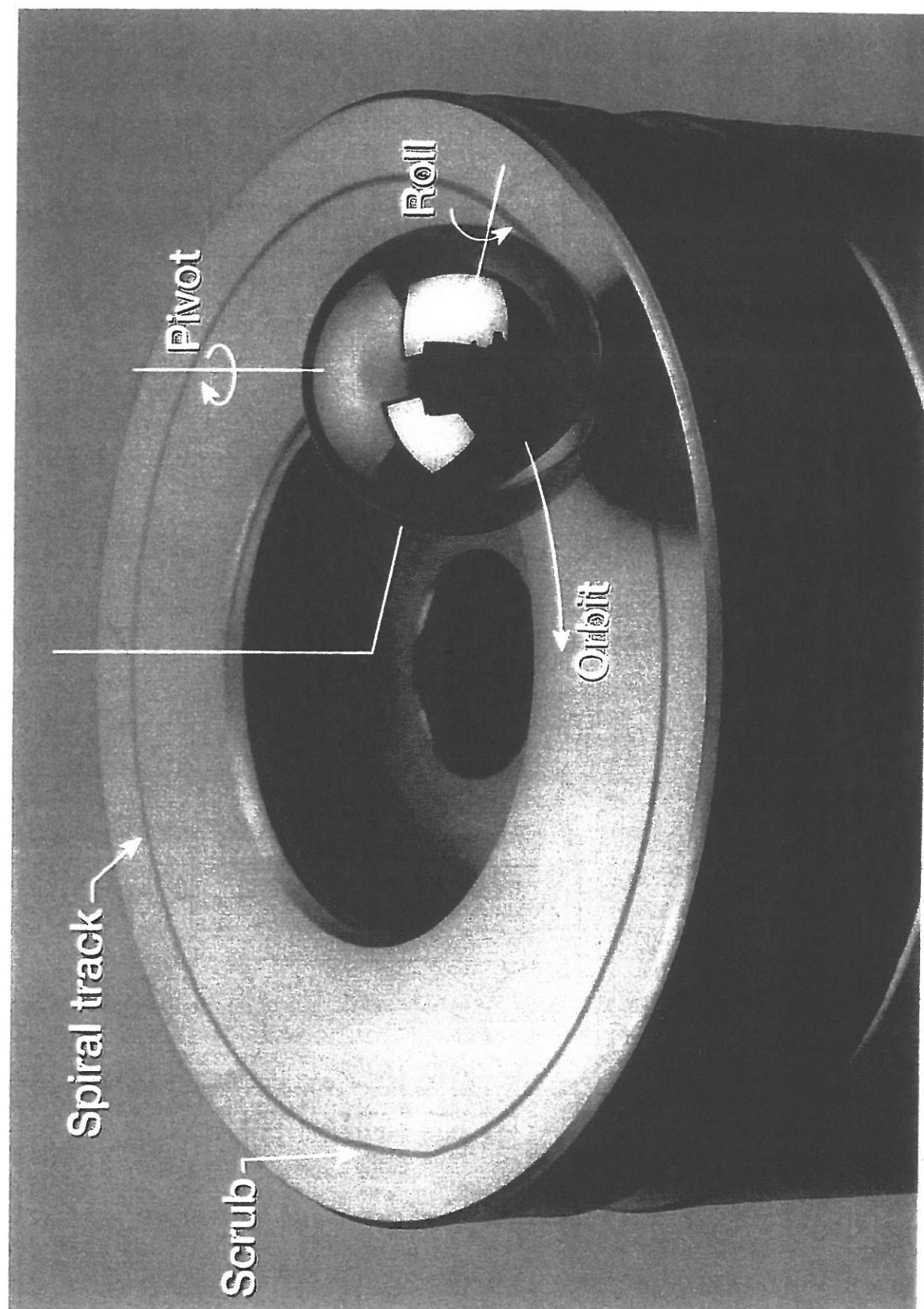


FIGURE 3